

[0005] In general, an optical wavelength router has at least one input optical port and at least one output optical port. In an optical router, light may be transmitted from a specific input port to a specific output port only if the light has an appropriate wavelength. Complex WDM systems may require optical wavelength router components that are more complex than a multiplexer or a demultiplexer.

[0006] Planar lightwave circuit technology is one technology that may be used to implement an optical wavelength router. A planar lightwave circuit (PLC) is an application of integrated optics. In a PLC, light is restricted to propagate in a region that is thin (typically between approximately 1 μm and 30 μm) in one dimension, referred to herein as the lateral dimension, and extended (typically between 1 mm and 100 mm) in the other two dimensions. The plane in which the PLC is disposed is defined as the plane of the PLC. The longitudinal direction is defined as the direction of propagation of light at any point on the PLC. The lateral direction is defined to be perpendicular to the plane of the PLC. The transverse direction is defined to be perpendicular to both the longitudinal and the lateral directions.

[0007] In a typical example of a PLC, a slab waveguide comprises three layers of silica glass, a core layer lying between a top cladding layer and a bottom cladding layer. Channel waveguides are often formed by at least partially removing (typically with an etching process) core material beyond the transverse limits of the channel waveguide and replacing it with at least one layer of side cladding material that has an index of refraction that is lower than that of the core material. The side cladding material is usually the same material as the top cladding material. In this example, each layer is doped in a manner such that the core layer has a higher index of refraction than either the top cladding or bottom cladding. When layers of silica glass are used for the optical layers, the layers are typically deposited on a silicon wafer. Deposition processes may include, chemical vapor deposition (CVD), low pressure chemical vapor deposition (LP-CVD), and/or plasma-enhanced CVD (PECVD). As a second example, slab waveguides and channel waveguides comprise three or more layers of InGaAsP.

In this example, adjacent layers have compositions with different percentages of the constituent elements In, P, Ga, and As. As a third example, one or more of the optical layers of the slab waveguide and/or channel waveguide may comprise an optically transparent polymer. In this example, spin coating is one known film deposition method. Another example of a slab waveguide comprises a layer with a graded index such that the region of highest index of refraction is bounded by regions of lower indices of refraction. Graded index structures are commonly formed by dopant in-diffusion and have been used for LiNbO₃ waveguides. A doped-silica waveguide is usually preferred because it has a number of attractive properties including low cost, low loss, low birefringence, stability, and compatibility for coupling to fiber.

[0008] The arrayed-waveguide grating router (AWGR) is the preferred integrated optical router. An AWGR is a planar lightwave circuit comprising at least one input channel waveguide, an input planar waveguide, an arrayed-waveguide grating (AWG), an output planar waveguide, and at least one output channel waveguide. The edge of the input planar waveguide to which the input channel waveguides are attached is referred to herein as the input focal curve. The edge of the output planar waveguide to which the output channel waveguides are attached is referred to herein as the output focal curve. The arrayed-waveguide grating comprises an array of channel waveguides. The length of the i^{th} waveguide in the AWG is denoted as L_i . The angular dispersion that is provided by the AWG is determined in part by the difference in length between adjacent waveguides, $L_{i+1}-L_i$. The details of construction and operation of the AWGR are described in K. Okamoto, *Fundamentals of Optical Waveguides*, pp. 346-381, Academic Press, San Diego, CA, USA (2000). Each of the publications and patents referred to in this application are herein incorporated by reference in their entirety.

[0009] Fig. 1A depicts a conventional AWG router (AWGR) that acts as a demultiplexer **10**. A plurality of optical signals incident on one input optical port propagates through the device in the following sequence: the signals propagate through an input waveguide **12**, which is a input waveguide associated with the

input port; through an input slab waveguide **14**, which has the function of expanding the optical field in the transverse direction by diffraction; through the dispersive region **16** (namely, the array waveguide region) comprising an array of AWG waveguides **18** for modifying the direction of propagation for each wavelength constituent according to the wavelength of the constituent of the plurality of signals; through an output slab waveguide **20** for focusing the signals of different wavelength coupled from the dispersive region **16** into a plurality of predetermined positions in accordance with the predetermined wavelength difference; through a plurality of output waveguides **22** each associated with one output port. Fig. 1A depicts an AWG comprising six waveguide; however, any number of waveguides may be used and herein the number of waveguides used is referred to as “N.” A representative cross-section **30**, section 1B-1B, of waveguide gratings 16 from Fig. 1A is shown in Fig. 1B. Depicted are the substrate **34**, the bottom cladding **36**, the top cladding **38**, and waveguides comprising core material **31**, **32**, **33**. These waveguides are typically buried channel waveguides as shown and typically have a core region with uniform height and width as seen in first, intermediate, and Nth waveguides **31**, **32**, **33**, respectively. That is, the height of each waveguide of the grating is identical and the width of each waveguide of the grating is identical.

[0010] The dispersive property of the arrayed waveguide grating (AWG) region is attributable to the construction of the plurality of waveguides within the waveguide grating region such that adjacent waveguides have a predetermined length difference in accordance to the required dispersive properties of the dispersive region **16**, so that each signal at different wavelength coupled to and traveling over each channel waveguide **18** is provided with a phase difference from each other in accordance with the predetermined length difference. Each of the output waveguides **22** includes an input end **24**, which is arranged at a predetermined position, so that each separated signal at each wavelength is coupled to each output waveguide **22** and emerges from an output end **26** thereof.

[0011] In operation, the wavelength division multiplexed signals coupled into the input channel waveguide **12** expand into the input slab waveguide **14** by

diffraction. Then, the expanded signals are distributed to the channel waveguides **18** of the arrayed-waveguide grating **16**. Because each channel waveguide **18** of the arrayed-waveguide grating **16** has a predetermined waveguide length difference, each signal, after traveling over each channel waveguide **18** to the output slab waveguide **20**, has a predetermined phase difference according to its waveguide length difference. Since the phase difference depends on the wavelength of the signal, each signal at different wavelength is focused on a different position along the arc boundary **28** of the output slab waveguide **20**. As a result, separated signals, each having a different wavelength, are received by the plurality of output channel waveguides **22** and emerge therefrom, respectively.

[0012] The general principles and performance of an AWGR multiplexer are similar to the AWGR demultiplexer, except that the direction of propagation of light is reversed, the ports that act as inputs for the demultiplexer act as output ports for the multiplexer, and the ports that act as output ports for the demultiplexer act as input ports for the multiplexer.

[0013] Alternatively, an AWGR may comprise a plurality of output waveguides and a plurality of input waveguides; however, the general principles and performance are similar to the AWGR demultiplexer

[0014] Multiple routing functions including multiplexing and demultiplexing may be integrated on a silicon wafer to form a complex planar lightwave circuit (PLC). PLCs can be made using tools and techniques developed to extremely high levels by the semiconductor industry. Integrating multiple components on a PLC may reduce the manufacturing, packaging, and assembly costs per function.

[0015] One aspect of performance that is affected by the present invention is referred to as polarization dependent wavelength (PDW). This term, as well as a number of related terms, will now be defined. Spectral transmissivity (in units of dB) is defined as the optical power (in units of dBm) of substantially monochromatic light that emerges from the fiber that is coupled to the input port minus the optical power (in units of dBm) of the light that enters the optical fiber that is coupled to the output port of the optical router. Spectral transmissivity is a

function of the selected input port, the selected output port, the optical wavelength, and the polarization state of the incident light. When the incident light is in a polarization state called a “principle state of polarization,” the light will be in the same polarization state when it emerges from the device. For purposes of illustration only, the principle states of polarization are assumed to be independent of wavelength, input port and output port. It is understood that the invention is not so limited by this assumption. Again, for the purposes of illustration only, it will be assumed that the two principle states of polarization are the so-called transverse electric (TE) and transverse magnetic (TM) polarization states. The TE polarization state has an electric field that is predominantly aligned in the transverse direction and the TM polarization state has an electric field that is predominantly aligned in the lateral direction. Again, the invention is not so limited to devices having these principle states of polarization. Typically, the device performance is sensitive to the polarization state of the incident light is attributable to birefringence in the planar waveguides and the channels waveguides comprising the AWGR.

[0016] Fig. 2A depicts, for a particular input/output port combination, a first spectral transmissivity **40** associated with the TE polarization state and a second spectral transmissivity **42** associated with the TM polarization state. Typically, for values of spectral transmissivity that are larger than -10 dB, the TM spectral transmissivity is a replica of the TE spectral transmissivity that is shifted in wavelength by an amount that is referred to as the polarization dependent dispersion (PDD). Herein PDD is positive if the TM spectral transmissivity has a maximum that has a longer wavelength than the maximum of the TE spectral transmissivity and is negative otherwise. Polarization dependent wavelength (PDW) is defined herein as the absolute value of the PDD and is indicated in Fig. 2A. The curves for the spectral transmissivity **46, 48, 50, 52** for four input/output combinations are shown together in Fig. 2C. The absolute value of the difference between the spectral transmissivities for TE and TM polarization states is referred to as the spectral polarization dependent loss **44** and is depicted in Fig. 2B. The in-band PDL (IB-PDL) is the maximum value of the spectral polarization

dependent loss within a specified wavelength range called a “band” (typically a 0.2 nm range) for a particular input port and output port. The PDL for the device is typically defined as the largest value of IB-PDL among the values of IB-PDL for all input/output port combinations that are used in a particular application. To meet typical application requirements, it is critical for AWGRs to have a PDL value that is as close to 0 dB as possible.

[0017] In typical fiber optic communication systems, the polarization state of the light in the optical fiber may change in a manner that is uncontrolled and unpredictable. A change in the polarization state of the light in the fiber as it enters an AWGR will cause a change in the optical power that emerges from the AWGR that may be as large as the value of PDL for the AWGR. Because applications typically have little tolerance for such unpredictable changes in power, minimizing the PDL of an AWGR is highly desirable. PDL can be minimized by minimizing PDW. To meet typical requirements, PDW may be required to be less than 0.05 nm. For this reason, the design and manufacture of an AWGR that has a low value of PDW is highly desirable, yet very challenging.

[0018] There have been a number of techniques developed in an attempt to minimize PDW.

[0019] One approach to minimizing PDW involves selecting an optical layer design with minimum birefringence. In one example of this approach, U.S. Pat. No. 5,930,439 (Ojha *et al*) discloses a planar optical waveguide which reduces birefringence by doping the various optical layers so that the top cladding has a thermal coefficient of expansion that is close to the thermal expansion coefficient of the substrate. This approach is appropriate for an optical layer design comprising deposited silica layers with high concentrations of boron on a silicon substrate. Typically, this approach is impractical because the optical layers that are required for low birefringence are not capable of surviving standard reliability tests. For example, the optical layers may absorb water and subsequently form defects during a reliability test involving exposure to a temperature of 85°C and a relative humidity of 85%,

[0020] A second approach requires the introduction of an optical waveplate. For example, U.S. Pat. No. 5,901,259 (Ando *et al.*) teaches forming an optical waveplate by using a polyimide having a film thickness of 20 μm or smaller and further teaches the introduction of the waveplate onto an AWGR to reduce PDW. However, introducing a waveplate onto the AWGR typically reduces the performance of the AWGR with respect to insertion loss, directivity, and return loss and occasionally may cause the AWGR to break. Furthermore, the introduction of a waveplate increases the cost associated with the production of the AWGR.

[0021] A third approach to reducing PDW involves waveguides of the AWG that comprise three segments, a central segment and two flanking segments. A first flanking segment has a birefringence equal to that to the second flanking segment. The central segment has a birefringence that is different from the flanking segments. The boundary around the central waveguide segments defines a region that is referred to herein as a “patch.” By selecting lengths of the segments that are appropriate to values of birefringence of the segments, an AWGR can be realized with a small value for PDW. A variety of methods have been disclosed for providing for segments with differing values of birefringence. For example, C. G. M. Vreeburg, *et al.* in “A low-loss 16-channel polarization dispersion-compensated PHASAR demultiplexer,” IEEE Photonics Technology Letters, Vol. 10, No. 3, Pp. 382-384 (1998) discloses a method wherein the AWG comprises InP-based rib waveguides, and the central segment differs from the flanking segments with respect to width of the rib and thickness of the top cladding region above the rib. In general, waveguides may have birefringence contributions from two independent sources, namely, form birefringence and stress birefringence. For rib waveguides, changing the width of the waveguide changes the form birefringence but does not substantially change the stress birefringence. For buried channel waveguide, changing the width of the waveguide does not substantially change the form birefringence. The effect of the width of a buried channel waveguide on the value of stress birefringence in the waveguide is not well known in the prior art.

[0022] In a second example, U.S. Pat. No. 5,341,444 (Henry *et al.*) discloses a method that includes the deposition of a high index material, such as silicon nitride, in the patch region so that it is optically coupled to the waveguide segments below it and thereby provides the central segments with a birefringence that is different from the birefringence of the flanking segments.

[0023] In a third example, U.S. Pat. No. 5,623,571 (Chou *et al.*) discloses a method that includes reducing the thickness of the cladding material in the patch region so that waveguide segments below couple to the air above the top cladding in the patch region and thereby provide the central segments with a birefringence that is different from the birefringence of the flanking segments.

[0024] In a fourth example, C. K. Nadler *et al.* in "Polarization Insensitive, Low-Loss, Low-Crosstalk Wavelength Multiplexer Modules," IEEE Journal of Selected Topics in Quantum Electronics, Vol. 5, No. 5, pp. 1407-1412 (1999), discloses a method for compensating polarization sensitivity of AWGs by using "stress release" grooves etched on each side of the grating waveguide in the central region.

[0025] In all of these examples of this approach, extra process steps are required to provide the waveguide segments within the patch region with a birefringence that is different from the flanking waveguide segments. The disclosed methods are difficult to implement in practice because production of the required optical layers within the patch region within the required tolerances is difficult. The added complexity associated with the production of two different optical layer designs in two different regions also increases the cost of production. Despite the approaches above, PDW remains a problem in current AWGR designs.

SUMMARY OF THE INVENTION

[0026] The present invention provides an arrayed waveguide grating with waveguides of unequal widths. Described herein is an arrayed waveguide grating where each waveguide of the grating preferably has a substantially uniform width, but the width of any single waveguide in the grating may be selected based on a

predetermined birefringence preferably required for the waveguide. Generally, the narrowest grating waveguide preferably has the longest overall length and the widest grating waveguide preferably has the shortest overall length. The remaining intermediate waveguides have widths that may be interpolated between the narrowest and widest waveguide gratings. With an appropriate width for each waveguide, an arrayed waveguide grating may be provided having a low polarization dependent wavelength.

[0027] Alternative waveguides with variable widths may also be incorporated. For example, waveguides having two segments with different widths may be utilized. Alternatively, waveguides having tapered ends may also be utilized; and waveguides that taper in an arc-like pattern may also be utilized depending upon the desired results.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] Fig. 1A schematically depicts a conventional AWG with waveguides of uniform width.

[0029] Fig. 1B depicts a cross-section from Fig.. 1A showing the waveguide widths.

[0030] Fig. 2A schematically depicts the spectral transmissivity for a particular input/output port combination of an AWGR. The spectral transmissivity for the TE and TM polarizations are illustrated. The polarization dependent wavelength (PDW) is indicated on the Fig.

[0031] Fig. 2B schematically depicts the spectral polarization dependent loss (PDL) and the in-band PDL.

[0032] Fig. 2C schematically depicts the spectral transmissivities for a single input port and four different output ports.

[0033] Fig. 3A schematically depicts a variation of an AWGR. In this variation, the width of each waveguide is independent of the distance along the waveguide.

[0034] Fig. 3B depicts a cross-section from 3B-3B of Fig. 3A showing the grating waveguides with unequal widths.

[0035] Fig. 4A schematically depicts a cross-section view of a buried channel waveguide comprising parallel top and bottom surfaces, and side surfaces that are not flat.

[0036] Fig. 4B schematically depicts a cross-section view of a buried channel waveguide comprising parallel top and bottom surfaces, and flat side surfaces that are not parallel.

[0037] Fig. 4C schematically depicts a cross-section view of a buried channel waveguide that has a substantially rectangular cross-section.

[0038] Fig. 5 schematically depicts a cross-section view of a rib waveguide.

[0039] Fig. 6 schematically depicts another variation of an AWGR. In this variation, the width of each waveguide varies only in the taper region.

[0040] Fig. 7A shows the distribution of PDD for a control group.

[0041] Fig. 7B shows the distribution of PDD for a first group.

[0042] Fig. 7C shows the distribution of PDL for the control group.

[0043] Fig. 7D shows the distribution of PDL for the first group.

[0044] Fig. 8A shows the spectral transmissivity of a first AWGR from the control group.

[0045] Fig. 8B shows the spectral transmissivity of a second AWGR from the control group.

[0046] Fig. 8C shows the spectral transmissivity of a first AWGR from the first group.

[0047] Fig. 8D shows the spectral transmissivity of a second AWGR from the first group.

[0048] Fig. 9A shows the spectral transmissivity curves for several output ports of one AWGR of the control group.

[0049] Fig. 9B shows the spectral transmissivity curves for several output ports of one AWGR of the first group.

[0050] Fig. 10 schematically depicts another variation of an AWGR.

[0051] Fig. 11 schematically depicts another variation of an AWGR.

[0052] Fig. 12 schematically depicts another variation of an AWGR.

[0053] Fig. 13 schematically depicts another variation of an AWGR.

[0054] Fig. 14 schematically depicts another variation of an AWGR.

DETAILED DESCRIPTION OF THE INVENTION

[0055] Turning now to the drawings and referring initially to Fig. 3A, there is depicted one variation of the inventive AWGR 60. AWGR 60 may comprise at least one input waveguide 62, an input planar waveguide 64, an arrayed waveguide grating (AWG) 66, an output planar waveguide 68, and at least one output waveguide 70. An AWGR that operates as a demultiplexer may require a plurality of output waveguides 70 and an AWGR that operates as a multiplexer may require a plurality of input waveguides 62. The AWG may comprise a plurality of waveguides 66. An arbitrary number of curved surfaces, herein referred to as “normal surfaces” may be defined such that all waveguides of the AWG intersect the normal surfaces at normal incidence, i.e., such that the angle between the waveguide and the normal surface is about 90°. Representative examples of normal surfaces are depicted as 78, 80, 82. A view of the AWGR in the normal surface is a cross-section view. In the present invention, the location where the AWG intersects at least one normal surface, at least one of the waveguides of the AWG preferably has a birefringence value that is different from the birefringence value from at least one other waveguide of the AWG. In this context, “birefringence value” refers to the birefringence value of the fundamental guided mode of the waveguide. The birefringence values of the waveguides are significant because PDW of the AWG depends on the birefringence values of the waveguides.

[0056] For a typical channel waveguide, the birefringence value is a function of the refractive indices of the materials that comprise the waveguide and the dimensions and shapes of various regions that comprise the waveguide. As an example, detailed discussion is provided for the variation in which the waveguides comprise three materials, namely the core material, the bottom cladding material, and the top cladding material, each with a refractive index that is uniform throughout the material. However, the invention is not so limited, and may apply,

for example, to waveguides that comprise any number of materials, each with a uniform refractive index, or alternatively, it may apply to graded index waveguides. It is preferred that the difference in birefringence values of different waveguides of the AWG may be attributable to differences in the shape and dimensions of the core regions of the waveguides. It is preferably that at least one of the waveguides of the AWG differs in cross-section from at least one other waveguide of the AWG.

[0057] For a typical buried channel waveguide, as illustrated in Fig. 4A, the core **94** has a shape such that it comprises a bottom surface **96** that is substantially flat, a top surface **98** that is substantially flat and substantially parallel to the bottom surface, and two side surfaces **100**, **102**. The distance between the top surface of the core region and the bottom surface of the core region is referred to herein as the height, h , of the waveguide at a particular cross-section. When referring to a buried channel waveguide, the cross-sectional area of the core region of the waveguide divided by the height of the waveguide at a particular cross-section is referred to herein as the width of the waveguide.

[0058] Fig. 4B depicts a buried channel waveguide **104** comprising a core region **106** with flat sides **108** and Fig. 4C, depicts a buried channel waveguide **110** with a substantially rectangular cross-section. Although it is preferred that the AWG waveguides comprise buried channel waveguides, the invention is not so limited and the AWG waveguides may comprise other waveguide types, for example, the AWG waveguides may comprise rib waveguides **112**, **112'**, **112''** where each waveguide **112**, **112'**, **112''** may have a different corresponding height, h_1 , h_2 , h_3 , respectively, as depicted in Fig. 5. In at least one cross-section view, at least one of the waveguides of the AWG may preferably differ in width from at least one other waveguide of the AWG. Providing the at least one waveguide with a birefringence value that is different from at least one other waveguide by providing the respective waveguides with appropriate widths is preferred; however, it is also possible to produce waveguides having different heights or different refractive indices in accordance with the principles disclosed herein by, e.g., masking some but not all of the waveguides of the grating such

that each waveguide is exposed to different etch conditions or dopant diffusion conditions to provide waveguide cores of different heights, as shown in Fig. 5, or refractive index values respectively.

[0059] In one variation, at least one of the waveguides of the AWG has an average width that preferably differs from the average width of at least one other waveguide of the AWG. In this context, “average width” refers to the average taken over a substantial portion of length of the waveguide and is defined more clearly in the text and mathematical expressions that follow. As shown in Fig. 3A, the longest waveguide **76** is preferably the narrowest relative to the other waveguides in grating **66**. It is further preferred for the core to be substantially rectangular in the cross-section view, as illustrated in Fig. 3B. A representative cross-section **71**, section 3B-3B, of waveguide gratings **10** from Fig. 3A is shown in Fig. 3B. There the waveguides are depicted with unequal widths, as seen in first, intermediate, and Nth waveguides **72**, **74**, **76**, respectively. Also depicted are substrate **88**, bottom cladding **90**, and top cladding **92** in which waveguides **72**, **74**, **76** are disposed. Again as shown in this variation, the longest waveguide **76** is preferably the narrowest relative to the other waveguides in grating **74** and **76**. And waveguide **72** is preferably the widest waveguide. Intermediate waveguides **74** may each have a width that progressively becomes narrower with each adjacent waveguide from widest waveguide **72** to narrowest waveguide **76**. This variation depicts AWGR **60** having four waveguides in grating **66**, but the number of waveguides here is merely exemplary and any number of waveguides may be utilized in practice. Likewise, any number of waveguides may be used such that the principles set forth herein may be applied. AWG as shown in Figs. 3A and 3B may be manufactured by any number of conventional methods as discussed below.

[0060] As generally set forth, a method of controlling birefringence in, e.g., an arrayed waveguide grating, in accordance with the present invention may comprise first transmitting a signal, e.g., a light signal, into the input end of a first waveguide which may have a constant width and a certain length. The signal may also be transmitted into at least a second waveguide which preferably has a width

narrower than the width of the first waveguide and a length longer than the length of the first waveguide. As the number of waveguides increase, their corresponding widths preferably decrease and corresponding lengths preferably increase in accordance with the principles discussed herein.

[0061] As discussed above, in making waveguide gratings of variable widths, any number of manufacturing methods may be utilized. Producing, e.g., multiplexers and demultiplexers, may be integrated on, e.g., a silicon wafer to form a complex PLC. PLCs may be made using the tools and techniques developed to extremely high levels by the semiconductor industry.

[0062] In a typical embodiment, as shown in Fig. 3A, the slab waveguides **14** and **20** may be comprised of at least three layers of doped silica deposited on a silicon wafer, namely, a bottom cladding layer that is approximately 5 μm to approximately 50 μm thick, a core layer that is approximately 5 μm to approximately 12 μm thick and a top cladding layer that is approximately 5 μm to approximately 50 μm thick. In a typical variation the core layer may have a refractive index that is larger than the refractive index of the bottom cladding between approximately 0.02 and 0.2 and the refractive index of the bottom cladding is between approximately 1.4 and 2.2 as measured in the wavelength range between about 1520 nm and about 1600 nm. However, the invention is not so limited and may be applied to, e.g., integrated optical routers comprising waveguides that are comprised of other materials such as InGaAsP, silicon, LiNbO₃, or polymer. Furthermore, the slab waveguide may comprise more than three optical layers or may comprise a graded index layer. It is preferably that the input/output slab waveguides and/or the input/output waveguides are single mode waveguides, i.e., only the fundamental mode is guided by the waveguide.

[0063] The theory related the polarization dependence as it applies to a conventional AWGR and as it applies to the present invention is presented below. The spectral transmissivity I depends on T , which is the transfer function associated with the propagation of light from a first curve, referred to herein at the "curve A" to a second curve, referred to herein as the "curve B." At least some part of the AWG is preferably between curve A and curve B. A representative

example of curve A is shown as **82** in Fig. 3A and a representative example of curve B is shown as **78**. In a second example, curve A **84** may be located at the interface between the AWG **66** and the input planar waveguide **64**, and curve B may be located at the interface between the AWG **66** and the output planar waveguide **68**. An expression for the transfer function is given by H. Yamada, K. Okamoto, A. Kaneko, and A. Sugita, *Dispersion Resulting From Phase And Amplitude Errors In Arrayed-Waveguide Grating Multiplexers-Demultiplexers*, Optics Letters, vol. 25, no. 8, pp. 569-571 (2000). Accordingly, transfer function may be given by

$$T = \sum_{i=1}^N a_i \exp(j\phi_i) \exp(jk_0 OPL_i) \quad (1)$$

where N is the number of waveguides in the AWG and OPL_i is the optical path length along the i th waveguide of the AWG between curve A and curve B; k_0 is the value of $2\pi/\lambda$, where λ is the wavelength of the light in vacuum that enters the input port of the AWGR; a_i and ϕ_i are real numbers that are determined in part on which input port and output port are being used and also determined in part by how light propagates from the input port of the AWGR to curve A. Variables a_i and ϕ_i may further be determined in part by how light would propagate from the output port to curve B if the direction of propagation of light were reversed with respect to the intended application. To simplify further discussion, it may be assumed that curve A and curve B are circular arcs. It may further be assumed that the input waveguide couples light into the input planar waveguide at a location that is centered on a point that is the center of curvature of curve A. It may further be assumed that the output waveguide couples light from the output planar waveguide at a location that is centered on a point that is the center of curvature of curve B. For an ideal Gaussian AWGR, ϕ_i has the same value for all waveguides of the AWG, i.e., ϕ_i is independent of i . The relationship between I and T is

$$I = T T^*, \quad (2)$$

where T^* is the complex conjugate of T .

[0064] Generally in Eq. 1, a_i , ϕ_i and OPL_i are dependent on the polarization of light. To simplify further discussion, a_i may be assumed to be independent of polarization; however, the invention is not limited to this assumption. Referring to the principle states of polarization as TE and TM, we may associate ϕ_i^{TE} , ϕ_i^{TM} , OPL_i^{TE} and OPL_i^{TM} with the values of ϕ_i and OPL_i for the TE and TM polarization states, respectively. Eqs. 1 and 2 indicate that I may have the same value for both polarizations of light (i.e. the AWGR will have zero PDW) if

$$OPL_i^{TE} + \phi_i^{TE} = OPL_i^{TM} + \phi_i^{TM} + \delta \quad (3)$$

where δ is an arbitrary constant. The value of δ has no effect on I ; it may be only important for δ to be independent of i . Equation 3 may be expressed in the alternative form

$$\Delta OPL_i^{TE} = \Delta OPL_i^{TM} + \Phi_i \quad (4a)$$

where

$$\Delta OPL_i^{TE} = OPL_{i+1}^{TE} - OPL_i^{TE} \quad (4b)$$

$$\Delta OPL_i^{TM} = OPL_{i+1}^{TM} - OPL_i^{TM} \quad (4c)$$

$$\Phi_i = \phi_{i+1}^{TM} - \phi_i^{TM} - \phi_{i+1}^{TE} + \phi_i^{TE} \quad (4d)$$

Eq. 4 is the criterion for zero PDW. It is preferred that, $\Phi_i = 0$; however, the invention is not so limited. The requirement expressed by Eq. 4 depends only on the difference in OPL between adjacent waveguides of the AWG. Consequently, the criterion for zero PDW (i.e., Eq. 4) may be satisfied even if the evaluation of OPL values expressed in equation 4 for any waveguide segment excludes a segment of each waveguide, provided that the each excluded segment has the same OPL. For example, the input tapers that couple light from the input planar waveguide may be excluded from the evaluation of OPL for each waveguide without affecting the interpretation of Eq. 4. In general OPL may be expressed by the equation

$$\begin{aligned} OPL_i^{TE} &= n_i^{TE} L_i \\ OPL_i^{TM} &= n_i^{TM} L_i \end{aligned} \quad (5)$$

where n_i^{TE} and n_i^{TM} refer to the values of the effective index of the fundamental mode of the waveguide averaged along the waveguide between curve A and curve B for TE and TM polarized light respectively. Mathematically, n_i^{TE} and n_i^{TM} may be expressed as

$$\begin{aligned} n_i^{TE} L_i &= \int_0^{L_i} n_{z,i}^{TE} dz_i \\ n_i^{TM} L_i &= \int_0^{L_i} n_{z,i}^{TM} dz_i \end{aligned} \quad (6)$$

where $n_{z,i}^{TE}$ and $n_{z,i}^{TM}$ are the effective indices at a distance z along the waveguide from curve A towards curve B for the TE and TM polarizations respectively.

Applying equations 5 and 6, equation 4 may be expressed as

$$L_i \Delta B_i + B_i \Delta L_i = \Phi_i \quad (7)$$

where $\Delta L_i = L_{i+1} - L_i$, $\Delta B_i = B_{i+1} - B_i$, and

$$B_i = n_i^{TM} - n_i^{TE} \quad (8)$$

or equivalently

$$B_i L_i = \int_0^{L_i} B_{z,i} dz_i \quad (9)$$

where

$$B_{z,i} = n_{z,i}^{TM} - n_{z,i}^{TE} \quad (10)$$

In one variation of the inventive AWG, the AWG satisfies equation 7.

[0065] Eq. 7 does not necessarily fully specify the design of the AWG. A typical additional constraining equation may be expressed as $L_i \Delta n_i + n_i \Delta L_i = \Psi_i$ so that the pair of equations that define the AWG is given by

$$L_i \Delta B_i + B_i \Delta L_i = \Phi_i \quad (11a)$$

$$L_i \Delta n_i + n_i \Delta L_i = \Psi_i \quad (11b)$$

where $2n_i = n_i^{TM} + n_i^{TE}$, $\Delta n_i = n_{i+1} - n_i$, and Ψ_i may represent any number of expressions. Typically,

$$\Psi_i = m\lambda_0 \quad (12)$$

where m is the grating order of the AWGR is 10 and is an optical wavelength that is typically the mean of the optical wavelengths that are intended to be transmitted

from one of the input ports to one of the output ports of the AWGR. An example of an alternative expression for Ψ_i is

$$\Psi_i = \begin{cases} m\lambda_0 \dots \text{for odd } i \\ (m+1/2)\lambda_0 \dots \text{for even } i \end{cases} \quad (13)$$

The above expression of Ψ_i provides for an AWGR with a passband that is wider than the passband of a Gaussian AWGR. U.S. Pat. No. 5,467,418 (C. Dragone) discloses other choices for Ψ_i that also provides for a passband that is wider than the passband of a Gaussian AWGR. In one variation of the inventive AWG, the AWG satisfies equations 7 and 11. In the preferred variation, the values of B_i and n_i may be adjusted to the desired values by adjusting the values of w_i where w_i are the values of the average widths of the waveguides, and where the average is taken along the length of the waveguides between curve A and curve B. Mathematically the average width along a waveguide w_i and the standard deviation of the width along a waveguide σ_i may be defined herein as

$$\begin{aligned} w_i L_i &= \int_0^{L_i} w_{z,i} dz_i \\ \sigma_i^2 L_i &= \int_0^{L_i} (w_{z,i} - w_i)^2 dz_i \end{aligned} \quad (14)$$

where $w_{z,i}$ is the width of the i th waveguide at a distance z along the waveguide from curve A towards curve B. B_i and n_i may be substantially varied by changing the width of the waveguide, which is not obvious in the prior art. That B_i and n_i may be varied by the required amount is discussed in further detail below.

[0066] For illustrative purposes only, the equations 7 and 11 are expressed below in an approximate manner such that the dependence of n_i and B_i is made explicit.

$$\begin{aligned} L_i \left(\frac{dB_i}{dw} \right) \Delta w + B_i \Delta L_i &= \Phi_i \\ L_i \left(\frac{dn_i}{dw} \right) \Delta w + n_i \Delta L_i &= \Psi_i \end{aligned} \quad (15)$$

In Eq. 15 it is implicit that the derivatives are evaluated at $w=w_i$. Eq. 15 is accurate to the extent that n_i and B_i have a linear dependence on w . Again for illustrative purposes only, Eq. 15 can be expressed as

$$\begin{aligned} L_i \left(\frac{dB_{z,i}}{dw_z} \right) \Delta w + B_i \Delta L_i &= \Phi_i \\ L_i \left(\frac{dn_{z,i}}{dw_z} \right) \Delta w + n_i \Delta L_i &= \Psi_i \end{aligned} \quad (16)$$

provided that $\left(\frac{dB_{z,i}}{dw_z} \right) = \left(\frac{dB_i}{dw} \right)$ and $\left(\frac{dn_{z,i}}{dw_z} \right) = \left(\frac{dn_i}{dw} \right)$, i.e., provided that $B_{z,i}$ and $n_{z,i}$

are linearly depend on w_z within the range of values for w_z that are used in the waveguides. In Eq. 16 it is implicit that the derivatives are evaluated at $w_z=w_{z,i}$. The values of w_i and L_i for all the waveguides of the AWG can be determined from Eqs. 15 as follows. Values of Φ_i and Ψ_i are assumed to be known as part of the design criteria. Values of w_1 and L_1 are chosen. Then the values of n_i , B_i , and their derivatives are evaluated for a width equal to w_1 . Eqs. 15 are then applied to determine w_2 and L_2 . The process is iterated to find all the values of w_i and L_i for $i=2, \dots, N$. Alternatively, Eqs. 16 may be applied in the same manner.

[0067] For illustrative purposes only, it is shown below that a closed form solution for Δw_i and ΔL_i may be obtained provided that ΔL_i is independent of i .

$$\begin{aligned} - \left(n_i \frac{dB_i}{dw} - B_i \frac{dn_i}{dw} \right) \Delta L &= \Phi_i \frac{dn_i}{dw} - \Psi_i \frac{dB_i}{dw} \\ - L_i \left(n_i \frac{dB_i}{dw} - B_i \frac{dn_i}{dw} \right) \Delta w_i &= B_i \Psi_i - n_i \Phi_i \end{aligned} \quad (17)$$

The subscript on ΔL_i has been omitted to indicate that ΔL_i does not have a dependence on i in Eq. 17. As a typical example, it is further assumed that $\Phi_i=0$ and $\Psi_i=m\lambda_0$, then Eq. 17 may be expressed as

$$\begin{aligned} - \left(n_i \frac{dB_i}{dw} - B_i \frac{dn_i}{dw} \right) \Delta L &= -m\lambda_0 \frac{dB_i}{dw} \\ - L_i \left(n_i \frac{dB_i}{dw} - B_i \frac{dn_i}{dw} \right) \Delta w_i &= m\lambda_0 B_i \end{aligned} \quad (18)$$

One result that follows from Eq. 18 is

$$(dB_i/dw) \Delta w_i = - B_i \Delta L/L_i \quad (19)$$

Typically, $(dB_i/dw)/B_i$ is positive; hence it is preferred to arrange the average widths of the waveguides of the AWG such that the shortest waveguide is, on average, the widest and that the longest waveguide is, on average, the narrowest. Since B_i varies slightly as w_i changes, Eq. 19 suggests that variation for which ΔL_i is constant and $\Phi_i=0$ and $\Psi_i=m\lambda_0$ it is preferred to have waveguides with widths w_i that vary according to the number of the waveguide i in a manner that is slightly nonlinear.

[0068] The average widths of the waveguides of the AWG can be determined from either Eqs. 11, Eqs. 15, Eqs. 16, Eqs. 17, or Eqs. 18. For any particular waveguide that is required to have a particular average width, a number of variations are possible.

First Example

[0069] In one example, which is illustrated in Fig. 3A and 3B, the width of the waveguide may have a constant value throughout the entire length of the waveguide between the two planar waveguides, i.e., the width of the waveguide for any cross-section has a value that is equal to the required average value. In this variation, the standard deviation in width along each waveguide is substantially equal to zero. Typically, the values of optical path length that are used in the design calculations are based on the optical path lengths curve A 84 located at the juncture between the AWG region 66 and the input planar waveguide 64 and curve B 86 located at the juncture between the AWG region 66 and the output planar waveguide 68.

Second Example

[0070] In a second example, which is illustrated in Fig. 6, each waveguide of the AWG preferably has a constant width throughout the length of the waveguide except for a taper region where the AWG waveguide couples to the input planar waveguide (herein referred to as the “AWG input taper”) and for a taper region where the AWG waveguide couples to the output planar waveguide

(herein referred to as the “AWG output taper”). The variation **120** is similar to that shown in Fig. 3A in that grating **122** depicts first, intermediate, and Nth waveguides **124**, **126**, **128**, respectively. Also, a cross-sectional view 3B-3B of waveguides **122** is shown similar to Fig. 3B. However, in Fig. 6, the AWG input taper is between the input planar waveguide **64** and curve A **82**, and the AWG output taper is between the output planar waveguide **68** and curve B **78**. In this variation, it is preferred that each AWG input taper have a length that is substantially equal to the length of all other AWG input tapers and that each AWG output taper have a length that is substantially equal to the length of all other AWG output tapers. In this variation, it is further preferred that each AWG input taper have values of effective index $= n_{z,i}^{\text{TM}} - n_{z,i}^{\text{TE}}$ that vary linearly throughout the taper region according to the mathematical functions

$$n_{z,i}^{\text{TE}} = n_i^{\text{TE}} + (n_1^{\text{TE}} - n_i) z / L_I \quad (20a)$$

$$n_{z,i}^{\text{TM}} = n_i^{\text{TM}} + (n_1^{\text{TM}} - n_i) z / L_I \quad (20b)$$

where z is the distance along the waveguide from curve A towards the input planar waveguide and that each AWG output taper have values of effective index $n_{z,i}^{\text{TM}}$ and $n_{z,i}^{\text{TE}}$ that vary linearly throughout the taper region according to the mathematical functions

$$n_{z,i}^{\text{TE}} = n_i^{\text{TE}} + (n_0^{\text{TE}} - n_i) z / L_O \quad (21a)$$

$$n_{z,i}^{\text{TM}} = n_i^{\text{TM}} + (n_0^{\text{TM}} - n_i) z / L_O \quad (21b)$$

where z is the distance along the waveguide from curve A towards the input planar waveguide. Provided that $n_{z,i}^{\text{TM}}$ and $n_{z,i}^{\text{TE}}$ vary linearly with the width of the waveguide, Eqs. 20 and 21 are satisfied by a linear taper design. If Eq. 20 is satisfied, then OPL_i^{TE} and OPL_i^{TM} may be given by

$$\text{OPL}_i^{\text{TE}} = (L_I n_1^{\text{TE}} + L_O n_0^{\text{TE}}) / 2 + L_i n_i^{\text{TE}} \quad (22a)$$

$$\text{OPL}_i^{\text{TM}} = (L_I n_1^{\text{TM}} + L_O n_0^{\text{TM}}) / 2 + L_i n_i^{\text{TM}} \quad (22b)$$

where n_i^{TM} and n_i^{TE} now refers to the effective index values of the waveguide averaged over the section of the waveguide that excludes the tapers and L_i refers to the length along the waveguide from the midpoint of the input taper to the midpoint of the output taper. Applying Eq. 22, yields the result

$$L_i \Delta n_i + n_i \Delta L_i = \Psi_i \quad (23a)$$

which is the same as Eq. 11b, except that n_i now refers to an effective index value of the waveguide averaged over the section of the waveguide that excludes the tapers. Similarly, the following result may be obtained

$$L_i \Delta B_i + B_i \Delta L_i = \Phi_i \quad (23b)$$

which is similar to Eq. 11a, except that in Eq. 23a, B_i refers to the value of birefringence averaged over the section of the waveguide that excludes the tapers. Since Eq. 23 is formally equivalent to Eq. 11, the equations above that are derived from Eq. 11 may apply to this variation provided the modified interpretation of L_i , n_i and B_i are used.

Experimental Results of the Second Example

[0071] To demonstrate the utility of the present invention, a first group of AWGRs were fabricated that were based on the variation of Fig. 6 and a second group of additional conventional AWGRs were fabricated (referred to herein as the control group). The control group was similar in design to the first group except that all waveguides of the AWG had the same width. Three input waveguides were tested for each AWGR of each group. In both groups, 197 waveguides were used in the AWG. In the first group, the range of waveguide widths, i.e., value of $|w_N - w_1|$ was between 1 μm and 3 μm and the value of $w_N + w_1$ was between 15 μm and 18 μm . In the control group, the value of $|w_N - w_1|$ was less than 0.4 μm and the value of $w_N + w_1$ was between 15 μm and 18 μm . Three inputs were tested for each AWGR. At least 40 outputs were tested for each input waveguide of each AWGR. For the control group, the average value of PDD was 0.10 nm and the standard deviation of the values of PDD was 0.02 nm.

[0072] The distribution of the measured values of PDD and PDL for the control group is shown in Figs. 7A and 7C, respectively. For the control group, the average value of PDL was 0.58 dB and the standard deviation of the PDL values was 0.14 dB. For the first group, the average value of PDD was 0.00 nm and the standard deviation of the values of PDD was 0.02 nm. For the control group, the average value of PDL was 0.15 dB and the standard deviation of the PDL values was 0.05 dB.

waveguides, consequently, the OPL of segment **142** may be the same for all waveguides. Similarly, the width and length of segment **132** is preferably the same for all waveguides, consequently, the OPL of segment **132** may be the same for all waveguides. Similarly, the width and length of segment **140** is preferably the same for all waveguides, consequently, the OPL of segment **140** may be the same for all waveguides. Consequently, segments **130**, **132**, **140**, **142** may be excluded from the evaluation of the OPLs that enter into Eq. 4 and all equations derived from Eq. 4 without affecting the validity of Eq. 4 as the criterion for zero PDW. This variation is preferable if the evaluation of the input and output tapers of the second embodiment have OPLs that are different from one another and if the coupling between segments makes it difficult to evaluate the values of OPL in this region.

Fourth Example

[0075] In a fourth example, which is illustrated in Fig. 11, the *i*th waveguide may comprise two segments, a first segment **144** of width w_A and length $L_{A,i}$ and a second segment **146** of width w_B and length $L_{B,i}$. Because each segment may have a different width, each segment may consequently have a different effective index and birefringence. The average width, average effective index and average birefringence may be given by

$$w_i L_i = w_A L_{A,i} + w_B L_{B,i}$$

$$n_i L_i = n_A L_{A,i} + n_B L_{B,i}$$

$$B_i L_i = B_A L_{A,i} + B_B L_{B,i}$$

the average values of width, effective index and birefringence, in this variation preferably depend on *i* since $L_{A,i}$ and $L_{B,i}$ depend on *i*. Using the average values expressed above in Eq. 11 yields the following result

$$B_A \Delta L_{A,i} + B_B \Delta L_{B,i} = \Phi_i \quad (24a)$$

$$n_A \Delta L_{A,i} + n_B \Delta L_{B,i} = \Psi_i \quad (24b)$$

where n_A and n_B are the effective index values of first and second segments **144**, **146**, respectively, and B_A and B_B are the birefringence values for first and second segments **144**, **146**, respectively. All the values of $L_{A,i}$ and $L_{B,i}$ may be found in

the following manner. $L_{A,1}$ and $L_{B,1}$ are chosen. The values of n_A , n_B , B_A , and B_B may be determined from the waveguide structure of the respective segment. Eq. 24 may be applied to determine $L_{A,2}$ and $L_{B,2}$. Eq. 24 may then be applied iteratively until $L_{A,i}$ and $L_{B,i}$ values are found for $i = 2, \dots, N$.

Fifth Example

[0076] A fifth example is illustrated in Fig. 12. This example is similar to the third example, except that tapers are used on each waveguide between first segment **148** and second segment **150**. In this example, the taper design may be the same on all waveguides; therefore, the taper between segment A and segment B of each waveguide may be excluded from the evaluation of the OPL of each waveguide when applying Eq. 4 or any of the equations derived from it.

Sixth Example

[0077] A sixth example is illustrated in Fig. 13. In this example, the i th waveguide may comprise three segments, a central segment **154** and two flanking segments **152**, **152'**. A first flanking segment **152** preferably has a birefringence equal to that to the second flanking segment **152'**. The central segment **154** may have a birefringence that is different from the flanking segments **152**, **152'**. The boundary around the central waveguide segments **156** preferably defines a region that is referred to herein as a "patch." Such patches may typically be placed symmetrically about a midpoint of the relevant waveguides although the patches may individually be positioned anywhere along the waveguides. By selecting lengths of the segments that are appropriate to values of birefringence of the segments, an AWGR may be realized with a small value for PDW. The three segments **152**, **154**, **152'** may have widths w_A , w_B , and w_A , respectively, i.e., segments **152** and **152'** may have equal widths. Eq. 24 may be applied to this example provided that $L_{A,i}$ is interpreted as the length of segment **152** plus the length of segment **152'**. The number of waveguides and widths depicted here is merely exemplary and is not meant to limit the scope of this invention. Any number of waveguides, widths, and any number of patches having variable widths

may be utilized depending upon the desired application and remains within the scope of this invention.

Seventh Example

[0078] A seventh example is illustrated in Fig. 14. In this example, each waveguide of the AWG preferably has a width that continuously changes in an arc-like manner such that the waveguide may have a certain width at segment **158**. The width then preferably tapers in a gentle arc to a thinner segment **160**; and the waveguide then tapers gently to a width at segment **162**, preferably similar to segment **158**.

[0079] Although the present invention has been described with reference to particular variations, the description is only an example of the invention's application and should not be taken as a limitation. Various adaptations and combinations of features of the variations disclosed are now readily apparent to those of ordinary skill and are within the scope of the invention.